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Ship Materials Engineering Department
Research and Development Report

Damping Studies of Ceramic Reinforced Aluminum

by

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ABSTRACT

Ceramic reinforced aluminum alloys exhibit a unique combination of properties not found in monolithic aluminum alloys. The addition of high modulus ceramic particles to conventional aluminum alloys results in increased strength, elastic modulus and wear resistance. Because of these desirable engineering properties the damping capacity and storage modulus was measured as a function of ceramic volume fraction, temperature and frequency. Two Al-Si-Mg matrix composites were studied which included the wrought alloy 6061-T6 with 0 to 0.2 volume fraction of Al_2O_3 particles and the casting alloy A356-T6 with 0 to 0.2 volume fraction of SiC particles. They were manufactured by a process which is simpler and less costly than previously developed techniques for manufacturing metal matrix composites. The damping capacity and storage modulus were measured at 0.1, 1 and 10 Hz while the temperature was varied from -10 to 250°C. It was found that the cast matrix has a higher damping capacity than the wrought matrix above 100°C, possibly due to the presence of silicon in the matrix which lowers the grain boundary transition peak. The storage modulus and damping capacity increased with increasing reinforcement content. These results are consistent with other work done on ceramic reinforced aluminum alloys.

ADMINISTRATIVE INFORMATION

This report was prepared under the Quiet Alloys Program, part of the Functional Materials Block Program, Sponsored by Mr. Ivan Caplan, David Taylor Research Center (DTRC Code 0115). Work performed at the David Taylor Research Center was supervised by Dr. O. P. Arora, DTRC Code 2812, under Program Element 62234 N, Task Area RS34S94, Work Unit 1-2812-953. This report satisfies Milestone 94SR1/7.

INTRODUCTION

High damping structural materials have the potential to greatly reduce vibration and noise in many types of mechanical systems. There are currently few effective methods to damp longitudinal vibrations in mechanical systems. Conventional damping treatments which are effective on flexural vibrations do not effectively attenuate longitudinal vibrations because the damping material is not in the path of these vibrations. Fabrication of machinery systems from high damping material would be productive but most structural materials, while having excellent stiffness and strength, possess poor damping properties. Conversely, polymers with very high damping capacities have neither the strength nor the stiffness for use as structural

materials. Thus the search for high damping structural materials has increasingly focused on composite materials.

Ceramic reinforced aluminum alloys exhibit a unique combination of properties not found in monolithic aluminum alloys. The addition of high modulus ceramic particles to conventional aluminum alloys results in increased strength, elastic modulus, wear resistance, as well as other desirable engineering properties. In general, factors which increase stiffness in a given alloy system also lower the damping capacity. These composites were examined to determine the effect of the ceramic reinforcement on the damping capacity and stiffness of the alloy system.

EXPERIMENTAL PROCEDURE

The two Al-Si-Mg matrix composite systems studied were the wrought alloy 6061-T6 with 0 to 0.2 volume fraction of Al_2O_3 particles and the foundry alloy A356-T6 with 0 to 0.2 volume fraction of SiC particles. These materials were processed by incorporating either silicon carbide or alumina particles into molten aluminum alloys A356 and 6061 respectively. The particles were wetted by the molten aluminum by vigorously agitating the melt under vacuum. Once the ceramic particles are wet and uniformly distributed in the molten aluminum, the composite is then cast into its desired shape. This process is simpler and less costly than previously developed techniques for manufacturing metal matrix composites such as powder metallurgy, thermal spray, diffusion bonding, and squeeze casting, all of which are more energy or labor intensive. Table 1 shows the nominal compositions of these alloys.

Table 1. Nominal Matrix Composition.

| MATRIX | Si | Fe | Cu | Mn | Mg | Zn | Ti | all other elements | Al |
|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------------------|------|
| A356 | 6.50-7.50 | 0.15 max. | 0.20 max. | 0.10 max. | 0.30-0.45 | 0.10 max. | 0.20 max. | 0.15 tot. 0.05 max. | REM. |
| 6061 | 0.40-0.80 | 0.70 max. | 0.15-0.40 | 0.15 max. | 0.80-1.20 | 0.25 max. | 0.15 max. | 0.15 tot. 0.05 max. | REM. |

The A356 aluminum matrix composite is used primarily as foundry ingot where it is remelted and cast to near net shape components such as pistons, brake rotors, and golf club heads. The 6061 aluminum matrix composite is direct chill cast into billet and then extruded into shapes such as truck rails, driveshaft tubing, and bicycle rims.

The A356 aluminum matrix damping specimens were machined from sand cast 12mm x 35mm x 90mm rectangular bars. The bars were solution heat treated at 540°C for 12 hours with a subsequent water quench. The 6061 aluminum matrix damping specimens were direct chill cast into a 170mm diameter billet which was then extruded into a 18mm x 75mm rectangular bar. This material was then solution heat treated at 560°C for 2 hours with a subsequent water quench. The bars of the A356 and 6061 aluminum matrix were then machined into 1mm x 5mm x 35mm damping specimens and aged at 160°C for 24 and 16 hours respectively to reach the T-6 or peak hardness condition.

The samples were photographed at a magnification of 250x and hardness test were performed before and after the damping measurements in order to ascertain changes in the microstructure due to thermal cycling. Volume fraction and particle density measurements for each material were taken using a LECO 300 Metallograph at a magnification of 250x and a Bio Scan Optimas image analyzer. Twenty fields were taken and then averaged to determine relative volume fractions of each material. Image analysis was performed on the actual samples used for damping measurement in order to account for any inhomogeneities in the materials.

The damping capacity and storage modulus was measured with a Polymer Laboratories Dynamic Mechanical Thermal Analyzer (DMTA) using a fixed-guided cantilevered test configuration. In this configuration, shown in Fig. 1, the clamp on the left holds the sample to a stationary frame while the right clamp attaches the sample to the controlled drive shaft. When the samples are not firmly held, erroneous damping measurements may result due to slip between the sample and clamps. In order to minimize such errors, three-pronged clamps were used. A torque wrench was used to tighten the clamps in order to achieve consistent clamping.

The damping was measured by applying a small sinusoidal time-varying mechanical force to the drive shaft and measuring the displacement of the sample.. The phase angle, δ , of the lag between the applied load and the measured displacement was calculated. The tangent of δ is a measure of the damping capacity commonly called the loss factor. Comparison of the amplitude of the load and displacement signals yielded the storage modulus, E' . All samples were tested at three distinct frequencies of vibration: 0.1, 1, and 10 Hz. The dependence of $\tan \delta$ and E' on temperature was determined by vibrating the samples at 160 microstrain (maximum) while ramping the temperature 1°C per minute from -10 to 250°C and continually alternating the frequencies.

The values of E' were corrected to account for error which arose from end-effects at the clamping point of the beam. These effects are due to the uncertainty in the point at which the metal starts to bend in the grips. These "end corrections" are based on the measured modulus and are calculated from an empirically generated curve. Corrections to the $\tan \delta$ values were made to account for the friction between the air and the moving sections of the DMTA, including the sample, as the sample was vibrated. The correction factor is frequency dependent and for measured values of the loss factors below 0.01 it was necessary to correct the 10 Hz data. This was done by averaging the loss factor data values over a temperature range in which $\tan \delta$ was nominally flat. The average of the 1 Hz $\tan \delta$ data was then subtracted from the average of the 10 Hz $\tan \delta$ data and that number was subtracted from the uncorrected 10 Hz $\tan \delta$ values.

RESULTS

Photomicrographs of the unreinforced, 10 and 20 volume percent Al_2O_3 reinforced 6061 aluminum shown in Fig. 2 and the unreinforced and 20 volume percent SiC reinforced A356 aluminum shown in Fig. 3 show that the distribution of Mg_2Si is uniform in the 6061 aluminum matrix while primary silicon is found at interdendritic areas in the A356 aluminum matrix. This variation in distributions is due to the differing fabrication methods. These photographs are of the samples after damping tests had been performed. There was no difference between the

microstructures of the samples before and after the damping tests based on the hardness measurements.

The results of the quantitative image analysis are presented in Table 2. These results show that the volume fraction of particulates in the samples did not widely differ from the nominal volume fraction. The samples containing a larger volume fraction of particulates also contained larger diameter particles. The number density of the particulates decreased with increasing volume percent therefore the surface area of the particulates did not increase proportionally to the volume fraction. In fact there was little difference in the surface area density of the three reinforced samples.

Table 2. Results of Quantitative Image Analysis.

| Material | measured v/o particulate | | mean particulate diameter (μm) | | number of particles per mm^2 | | surface area per mm^2 (mm) | |
|-----------------------------|--------------------------|--------|---|--------|---------------------------------------|-----------------|-------------------------------------|--------|
| | 10 v/o | 20 v/o | 10 v/o | 20 v/o | 10 v/o | 20 v/o | 10 v/o | 20 v/o |
| Nominal Particulate Content | | | | | | | | |
| A356 | NA | 21.3 | NA | 17 | NA | 9×10^4 | NA | 4800 |
| 6061 | 9.6 | 19.4 | 10 | 25 | 12×10^4 | 4×10^4 | 3770 | 3140 |

The damping capacity of 6061 aluminum with 0, 0.1 and 0.2 volume fractions of Al_2O_3 particles is plotted against the storage modulus in Fig. 4. The loss factor in homogeneous rheologically simple material is a single valued function of storage modulus independent of the frequency and temperature at which the measurements were taken. This is the case for the three materials at low temperatures, however above 100°C the data is no longer single valued because there is a separation in the data taken at different frequencies. This is the result of the matrix softening with increasing temperature which slightly changes the particle-matrix interaction [1]. The curves are smooth, which indicates an absence of systemic error in the DMTA, but the scatter increases with increasing ceramic content. The modulus is greatly increased when Al_2O_3 is added and the damping capacity also increases. The damping capacity and storage moduli of

the 6061 aluminum matrix composites is plotted against temperature in Figs. 5 and 6. There is a distinct low temperature peak in the damping capacity of the monolithic sample which is also present in the data from the reinforced samples at lower temperatures although it is somewhat obscured by the scatter in these samples. The reinforced samples have a higher loss factor than the monolithic material with the difference increasing with increasing temperature. The damping capacity is decidedly frequency dependent above 100°C with the lowest frequency resulting in the highest loss factor. The loss factor of the 6061 aluminum matrix never exceeds 0.01 (high damping threshold) in the measured temperature range. With the addition of 10 v/o Al_2O_3 the temperature at which the material becomes high damping is between 180 and 235°C depending on the frequency. In the sample containing 20 v/o Al_2O_3 the temperature at which the material becomes high damping drops between 20 and 35°C to between 160 and 200°C again depending on the frequency. The room temperature storage moduli of the 6061 aluminum matrix samples with 0, 0.1 and 0.2 volume fraction Al_2O_3 are 51, 69 and 83 GPa respectively. The amount of increase is not a linear function of the ceramic content but rather the majority of the stiffening effect is achieved by the initial addition of Al_2O_3 . The values of the modulus reported by the manufacturer for the three composites are 67, 80 and 97 GPa respectively. The DMTA has recognized problems measuring the modulus of stiff materials and in this case the error was between 11 and 14 GPa. All three materials softened with increasing temperature. The storage modulus is frequency dependent and decreases with temperature more rapidly with increasing ceramic content.

The damping capacity of monolithic A356 aluminum and A356 aluminum with 0.2 volume fraction SiC is plotted versus the storage modulus in Fig. 7. The loss factor is a single valued function of storage modulus independent of the frequency and temperature only up to 50°C. This is again the result of matrix softening changing the particle matrix interaction. The curves show much less scatter than the data for the 6061 aluminum matrix samples. The addition of 0.2 volume fraction SiC increases the storage modulus by 15 GPa and the damping capacity shows a slight increase. The damping capacity and storage modulus of A356 aluminum

and A356 aluminum with 0.2 volume fraction SiC is plotted versus temperature in Figs. 8 and 9. The damping capacity is decidedly frequency dependent above 50°C with the lowest frequency resulting in the highest loss factor. The monolithic A356 aluminum becomes high damping between 165 and 236°C depending on the frequency. With the addition of 20 v/o SiC the temperature in which the composite becomes high damping drops between 10 and 20°C to between 150 and 220°C depending on the frequency. The room temperature storage moduli of monolithic and 0.2 v/o SiC A356 aluminum are 97 and 113 GPa respectively. The values of the modulus reported by the manufacturer for these two materials are 74 and 95 respectively. The error in the modulus measured by the DMTA was excessive for these materials, ranging between 18 and 23 GPa. Both samples softened with increasing temperature and the frequency dependence of the storage modulus is more evident than in the 6061 aluminum composites.

DISCUSSION

Monolithic Aluminum

At temperatures above 0.5 of the melting temperature and frequencies near 1 Hz polycrystalline metals exhibit an internal friction peak which has been associated with the relaxation of grain boundaries. The literature on grain boundary damping of aluminum contains numerous citations with regard to the relaxation mechanisms [2,3,4]. Grain boundary sliding, or grain boundary viscosity was first postulated by Kê and later by Mott. These authors proposed models in which the viscosity is related to the stress induced rearrangement of disordered atom groups within the grain boundary. A critical temperature is associated with the creation of these disordered atom groups. However, internal friction results showing a grain boundary-like relaxation in single crystals has cast doubt on these atomic models [5,6,7].

At present the most probable theoretical explanation for grain boundary damping is based upon the glide and climb of dislocations within the boundary zone [7]. The following expressions for the relaxation time were derived by Woigard et al. for dislocation motion within the plane of the grain boundary.

$$\tau_{GB} = k T \Lambda^2 L / [3 \beta G \Omega D_b b] \quad (1)$$

where k is Boltzmann's constant, T is absolute temperature, Λ is the mean spacing between pinning points, L is the mean spacing between grain boundary dislocations, β is a geometric constant, G is the shear modulus, Ω is the vacancy volume, D_b is the grain boundary diffusion rate and b is the grain boundary thickness.

Bhagat et al. [8] report a loss factor between 0.0015 and 0.0025 for 6061 aluminum below 1000 Hz measured using the logarithmic decrement technique. This value is about half of the value measured in this study but generally the logarithmic decrement technique results in a conservative value.

Particulate Reinforced Aluminum

Conflicting opinions presently exist with regard to the damping of particulate reinforced aluminum. Improved damping is often reported in trade journals as one of the attributes of this ceramic reinforced metal matrix composite, e.g. ref. [9]. However, the mechanism associated with the improved damping has not been fully investigated.

As mentioned above and illustrated in Figs. 5 and 8, the damping capacity is decidedly frequency dependent over only part of the temperature range measured. In the frequency insensitive range the particulates raise the damping capacity only slightly over that of the matrix. In the frequency dependent range the damping capacity is greatly increased over that of the matrix. These two phenomena are described separately below.

Frequency insensitive range

Wolfenden et al. [10] reported a loss factor of 0.0005, 0.0009 and 0.0014 for A357 with 10, 15 and 20 v/o SiC particulate reinforcement respectively. The measurements were made at 100 kHz using the PUCOT. The trends of Wolfenden's data is similar to the results of this study in the frequency insensitive part of the curve. In [11] the damping is attributed to the high concentrations of dislocations near the Al/SiC interfaces. Thermal stresses at the interfaces are induced on cooling the metal matrix composite and these stresses generate large numbers of dislocations. From Table 3 it can be seen that there is a larger mismatch in the coefficients of

thermal expansion in 6061 aluminum- Al_2O_3 system than in the A356 aluminum SiC system. However, damping is not a linear function of dislocation density. In fact Ledbetter et al. [11] reported a loss factor of 0.000075 for 6061 aluminum containing 30 v/o SiC measured at 90 kHz using the PUCOT. The low value of damping was explained by the pinning of the dislocations which could then only contribute slightly to internal friction.

Kinra [12] showed that in heterogeneous materials such as metal matrix composite a thermoelastic damping contribution may be realized from the interface between the metal matrix and the reinforcing ceramic phase. The thermoelastic contribution is local to the interface and is higher in the ceramic. This effect is a function of the area of the interfaces as well as the amount of difference in the density, coefficient of thermal expansion and specific heat per unit mass of the matrix and the reinforcement. The values for those quantities are listed in Table 3. Unlike classical thermoelastic damping, the damping due to heterogeneity uniformly decreases with increasing frequency.

Table 3. Thermal Properties of Constituents.

| Material | Density Mg/m^3 | Coefficient of Thermal Expansion $\mu\text{m/m K}$ | Specific Heat per unit mass J/kg K |
|-------------------------|----------------------------|--|---|
| aluminum | 2.7 | 23.6 | 900 |
| 6061 aluminum | 2.7 | 23.6 | 896 |
| A356 aluminum | 2.68 | 21.5 | 963 |
| Al_2O_3 | 3.7 | 4.5 | 880 |
| SiC | 3.1 | 3.2 | 860 |

The damping at a single interface of aluminum and Al_2O_3 in tension was calculated at 100 Hz by Kinra. The loss factor was 0.0002 in the aluminum and 0.0079 in the Al_2O_3 at the interface. The damping drops off quickly away from the interface. Based on the values in Table 3, 6061 aluminum with added Al_2O_3 should exhibit about the same damping as the aluminum- Al_2O_3 system and A356 with SiC should have slightly less damping. Therefore in theory, some

of the increased damping at low temperatures with increasing ceramic content is attributable to this effect.

Frequency dependent range.

The formulation in equation 1 of the grain boundary relaxation is of particular interest because it may be extended and applied to interfaces in heterogeneous solids. Particle effects on the grain boundary relaxation peak would suggest that the second phase interface simply affects the local dislocation density [13]. Thus the relaxation time is anticipated to decrease and the damping peak is expected to shift to a lower temperature. Additionally, as in all thermally activated relaxations, an increase in the frequency shifts the peak to higher temperatures as is observed in our data.

In Mori et al. [14] it was shown that the relaxation time is proportional to the grain size and that particles in the grain boundary lower the temperature of the internal friction peak by shortening the relaxation time by a factor of $(1 + \pi ar / \lambda^2)$. Here a is the grain boundary radius, r is the average radius of the particles in the grain boundary and λ is the interparticle spacing. Thus the ceramic particles lower the temperature at which the grain boundary relaxation occurs and the damping capacity of the composites are higher than the monolithic material at temperatures below the grain boundary relaxation peak. This effect is largest for large closely spaced particles and does not depend on the composition of the particle.

Bhagat et al. [15] reported that a SiC particulate reinforced Al-Cu alloy exhibited a damping peak at 1318 Hz with 0.035 loss factor. The measurements were made on a freely decaying cantilever beam vibrating in its primary bending mode. This represented a two fold increase in damping over similar unreinforced alloys; however, the peak could not be resolved in the data for the monolithic alloy. The trend of Bhagat's data is similar to the results of this study in the frequency dependent region.

Classic thermoelastic damping arises from non uniform strain in a material either due to bending or non-homogeneous material. In [16] the loss factor in an Al-Mg mechanically alloyed composite beam is given as 0.00035 in the first mode, while the loss factor of 6061 with 15 v/o

SiC is 0.0007. The improved damping was qualitatively explained as a result of thermoelastic damping. It happened that the SiC composite was an optimal thickness for thermoelastic damping whereas the unreinforced alloy was not. At frequencies where thermoelastic damping was negligible there was no difference in damping between reinforced and unreinforced aluminum. In our study the thickness and the thermal properties of our materials was sufficiently similar to avoid complications of this kind.

CONCLUSIONS

Addition of Al_2O_3 to 6061 and SiC to A356 aluminum produces a composite with increased modulus. The amount of increase in stiffness is not a linear function of the ceramic content but rather the majority of the stiffening effect is achieved by the initial addition of ceramic.

The damping capacity of the composites is higher than the monolithic material due to the increase in dislocation density, heterogeneous thermoelastic damping, and lowering of the grain boundary relaxation temperature in the matrix.

The methods to optimize these effects are clearly documented in the literature. The damping due to dislocation increase is optimized by maximizing the mismatch of the thermal expansion coefficient between the matrix and reinforcement phase. The damping due to heterogeneous thermoelastic damping is maximized by choosing the matrix and reinforcement phase with widely different thermal properties and by maximizing the surface area of the reinforcement. The damping at room temperature due to the lowering of the grain boundary relaxation temperature is greatest when the grain boundary damping peak is lowered to room temperature. The effect of the particulates on the temperature of this peak is greatest with large closely spaced particles.

High damping structural materials can be achieved by suitably designing particulate reinforced metal matrix composites.

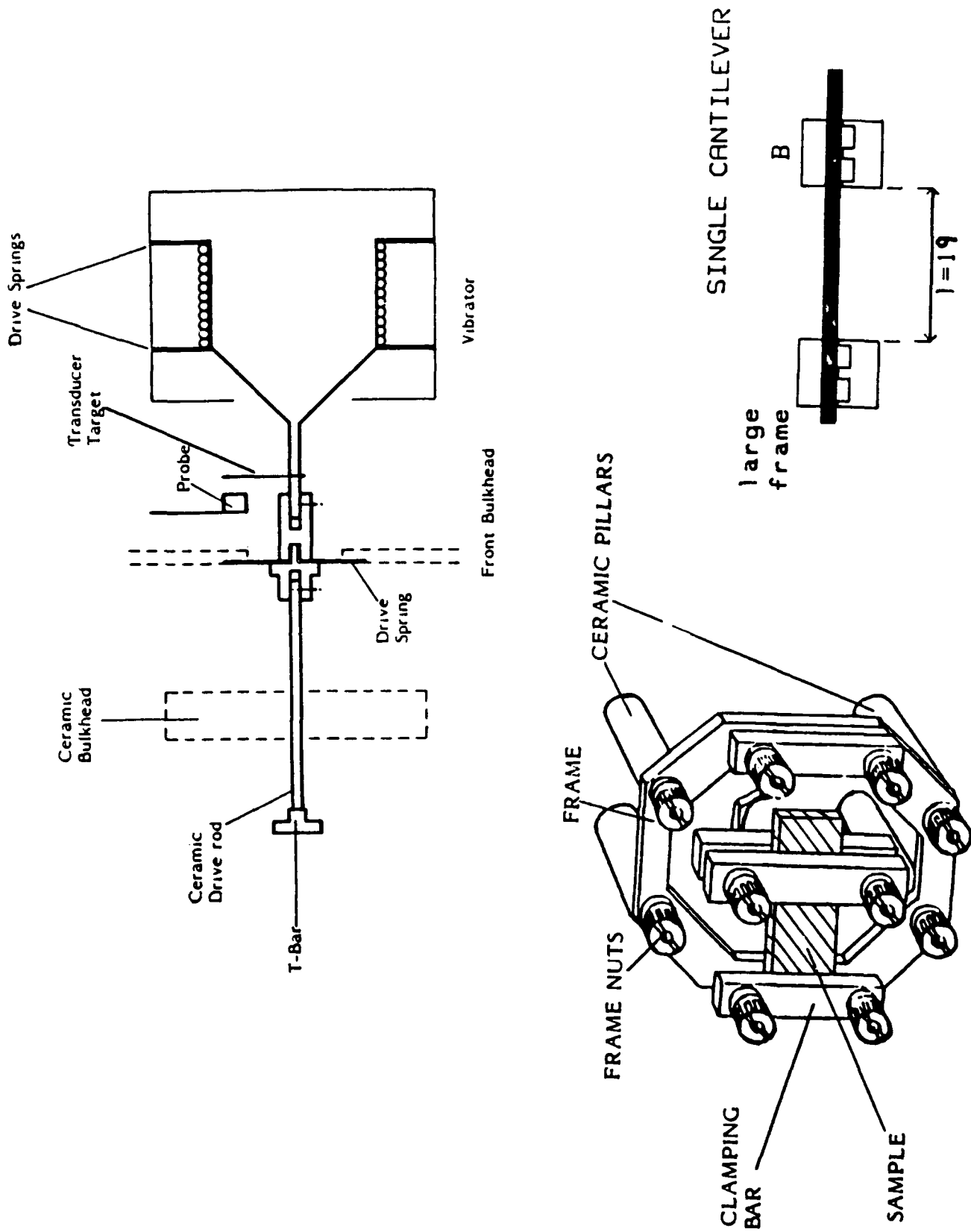


Fig. 1. Dynamic Mechanical Thermal Analyzer: grip setup.

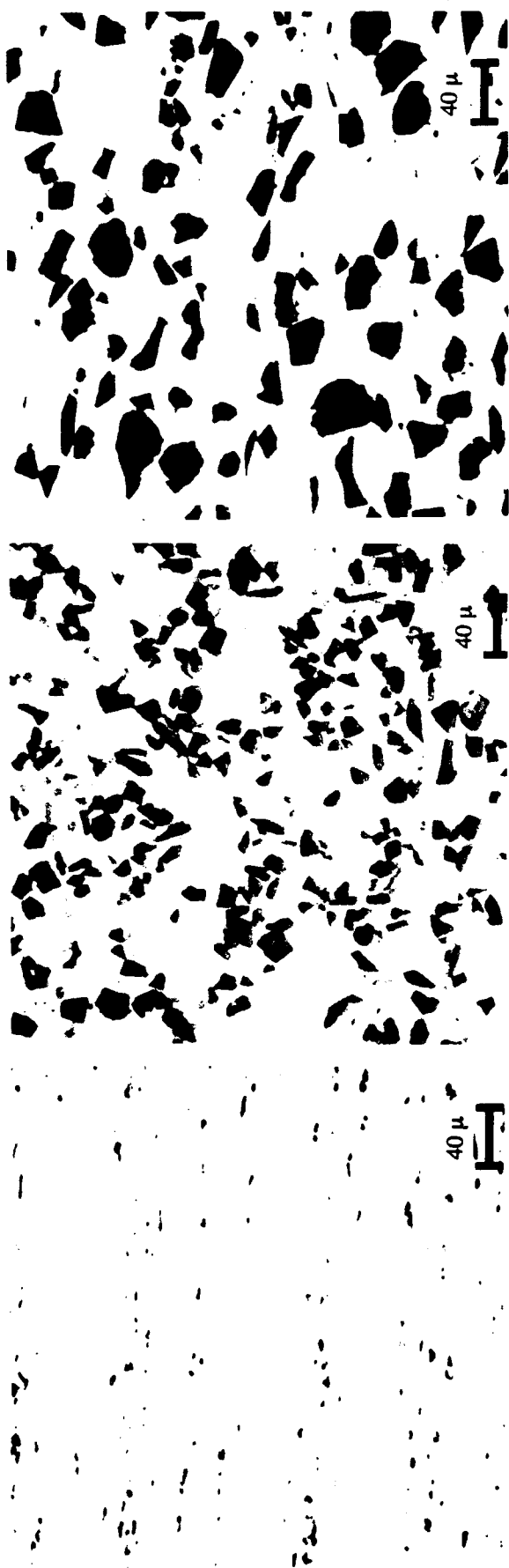


Fig. 2. Microstructure of 6061 aluminum with 0, 10, and 20 v/o Al_2O_3 .

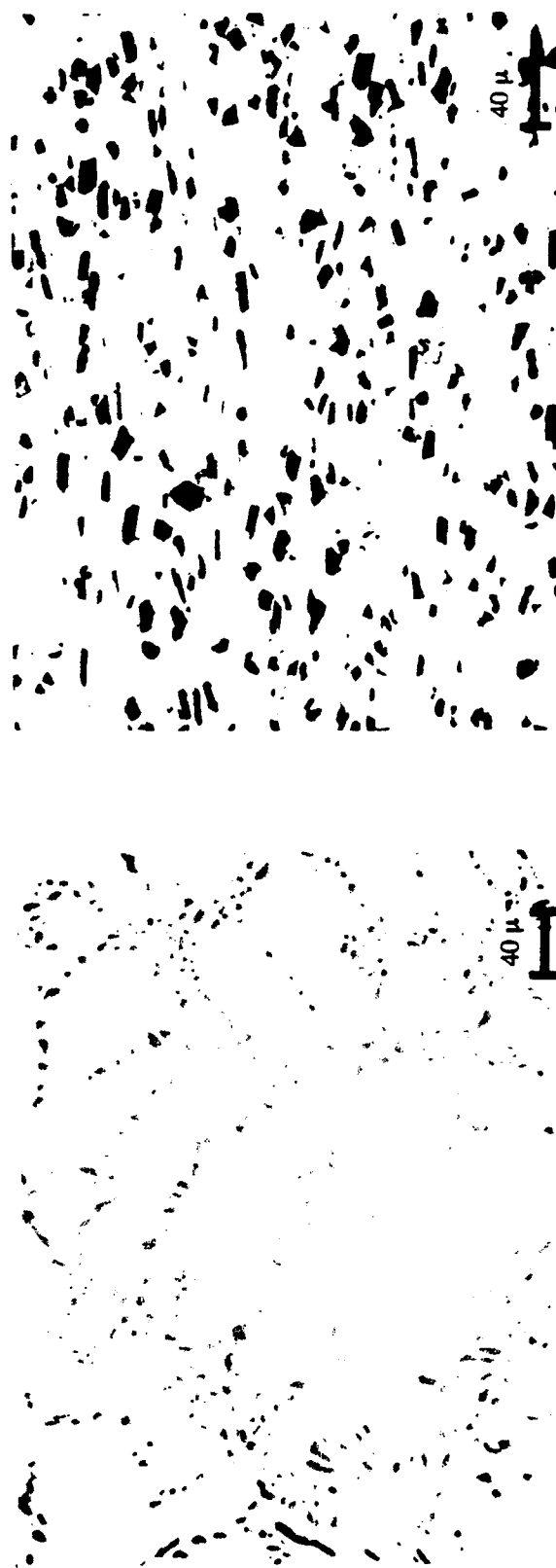


Fig. 3. Microstructure of A356 aluminum with 0 and 20 v/o SiC .

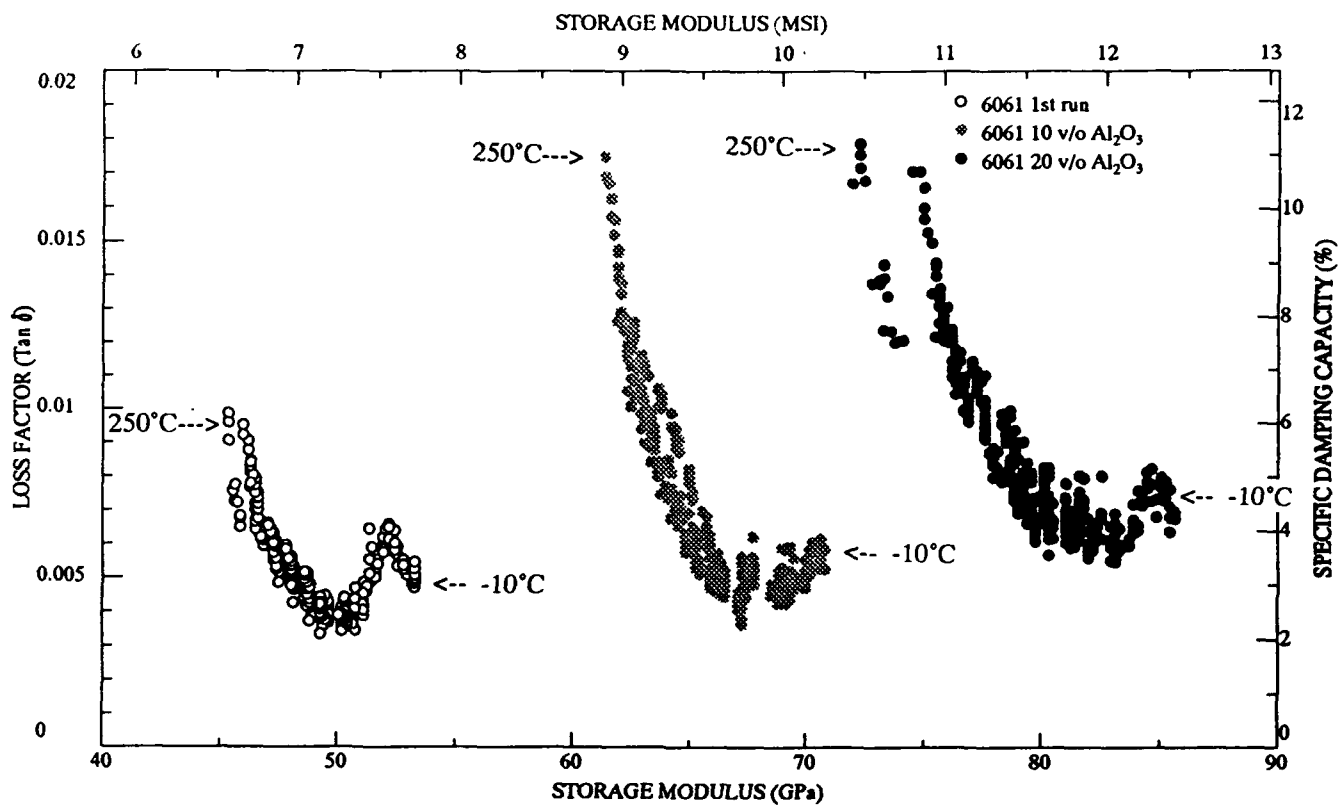


Fig. 4. The effect of temperature on the damping capacity and the storage modulus of 6061 aluminum matrix composites measured at 0.1, 1, and 10 Hz from -10 to 250°C.

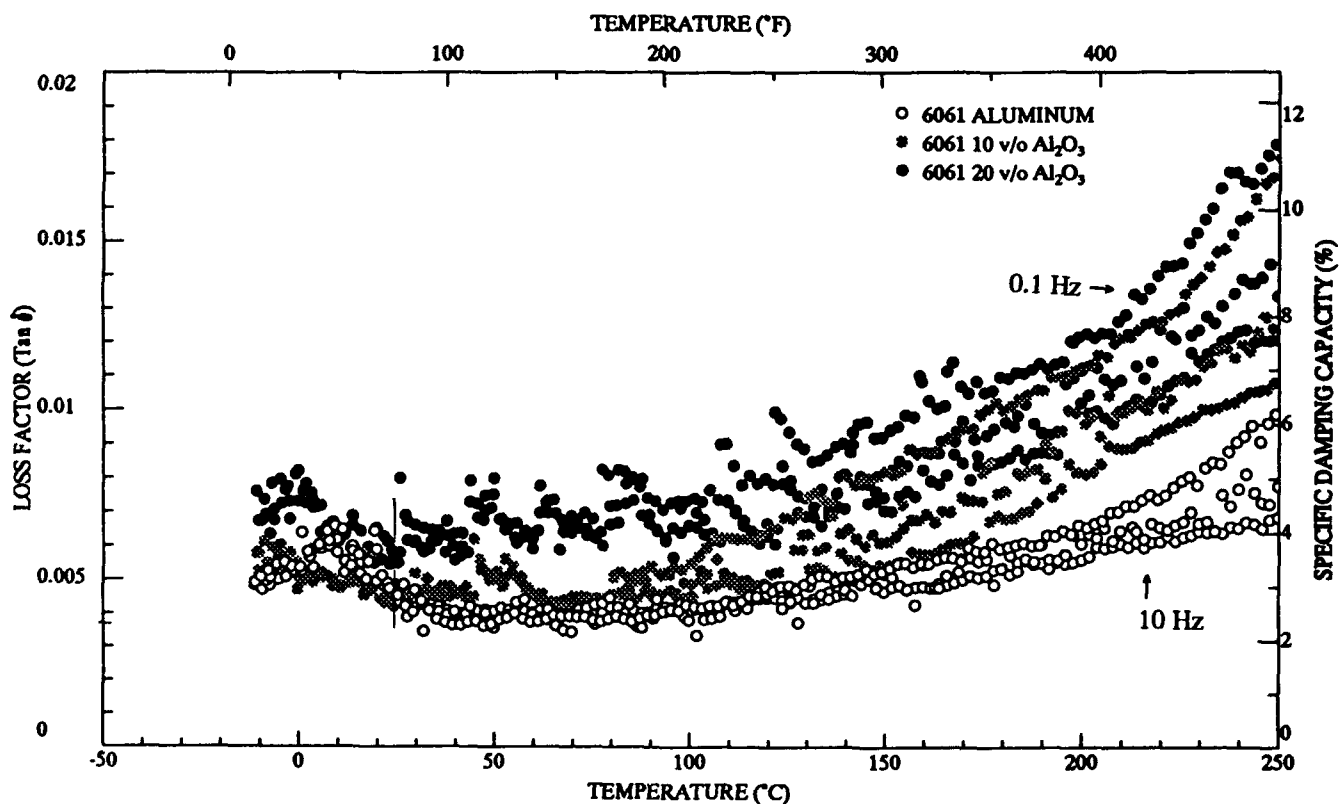


Fig. 5. The effect of frequency on the damping capacity of 6061 aluminum matrix composites measured at 0.1, 1, and 10 Hz with the temperature increasing 1°C per minute.

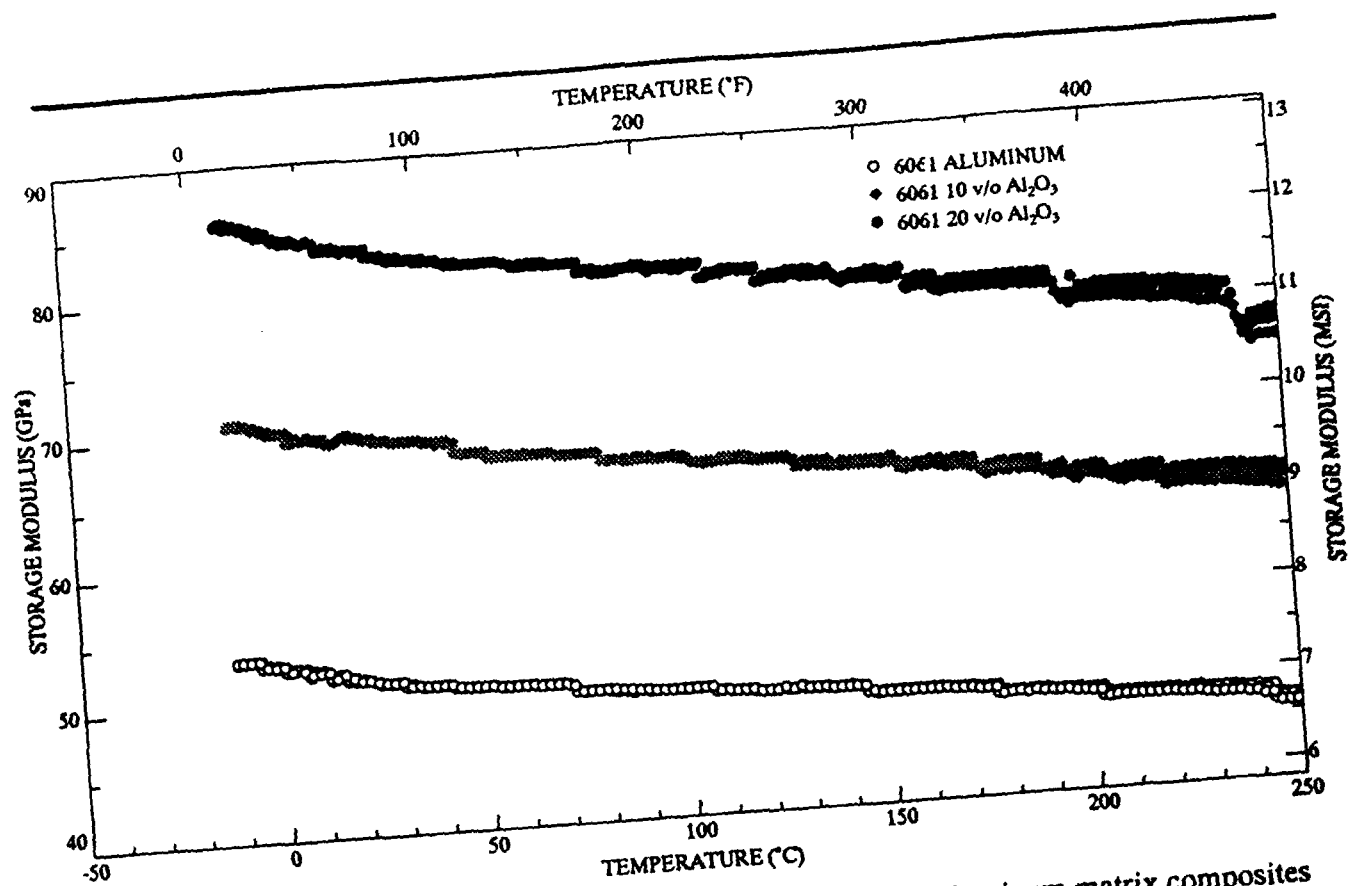


Fig. 6. The effect of frequency on the storage modulus of 6061 aluminum matrix composites measured at 0.1, 1, and 10 Hz with the temperature increasing 1°C per minute.

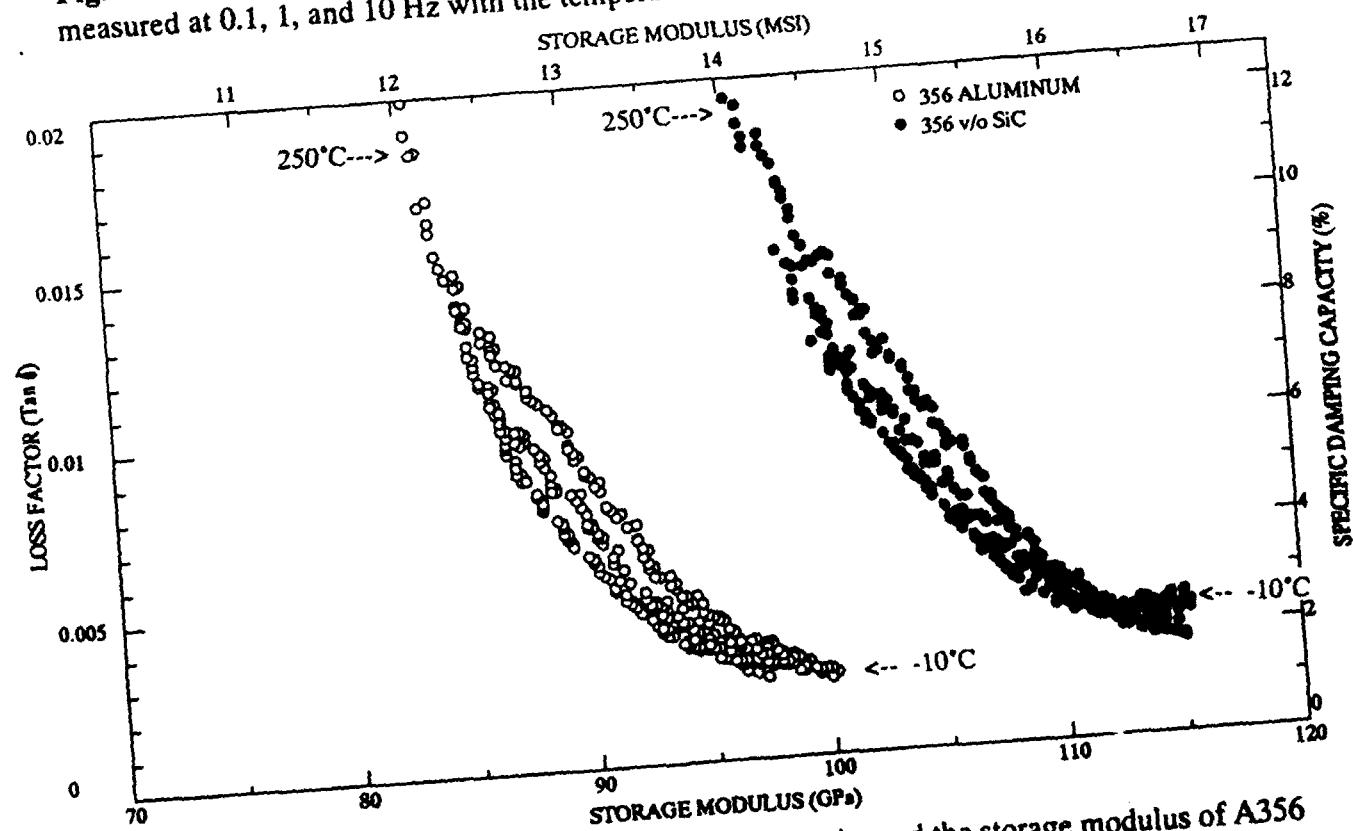


Fig. 7. The effect of temperature on the damping capacity and the storage modulus of A356 aluminum matrix composites measured at 0.1, 1, and 10 Hz from -10 to 250°C.

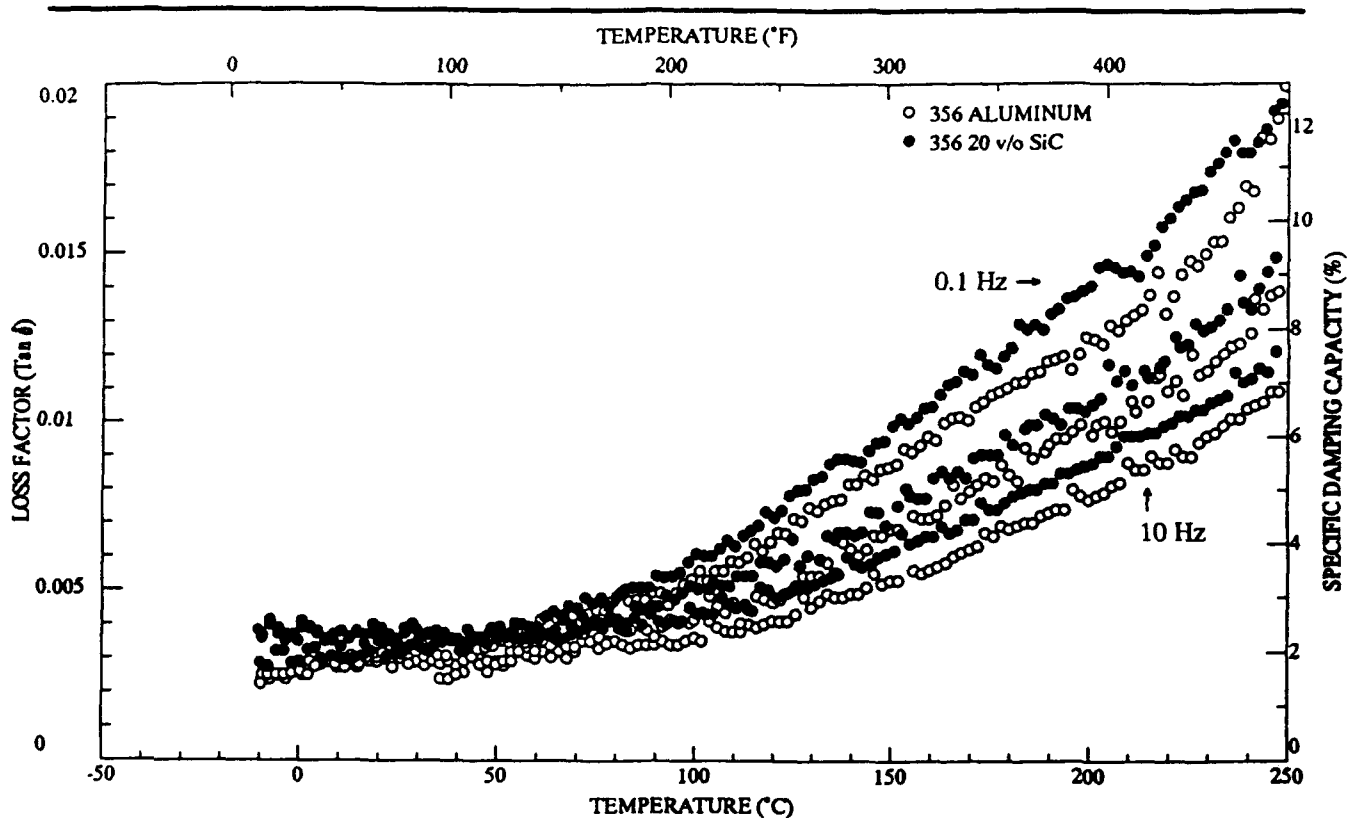


Fig. 8. The effect of frequency on the damping capacity of A356 aluminum matrix composites measured at 0.1, 1, and 10 Hz with the temperature increasing 1°C per minute.

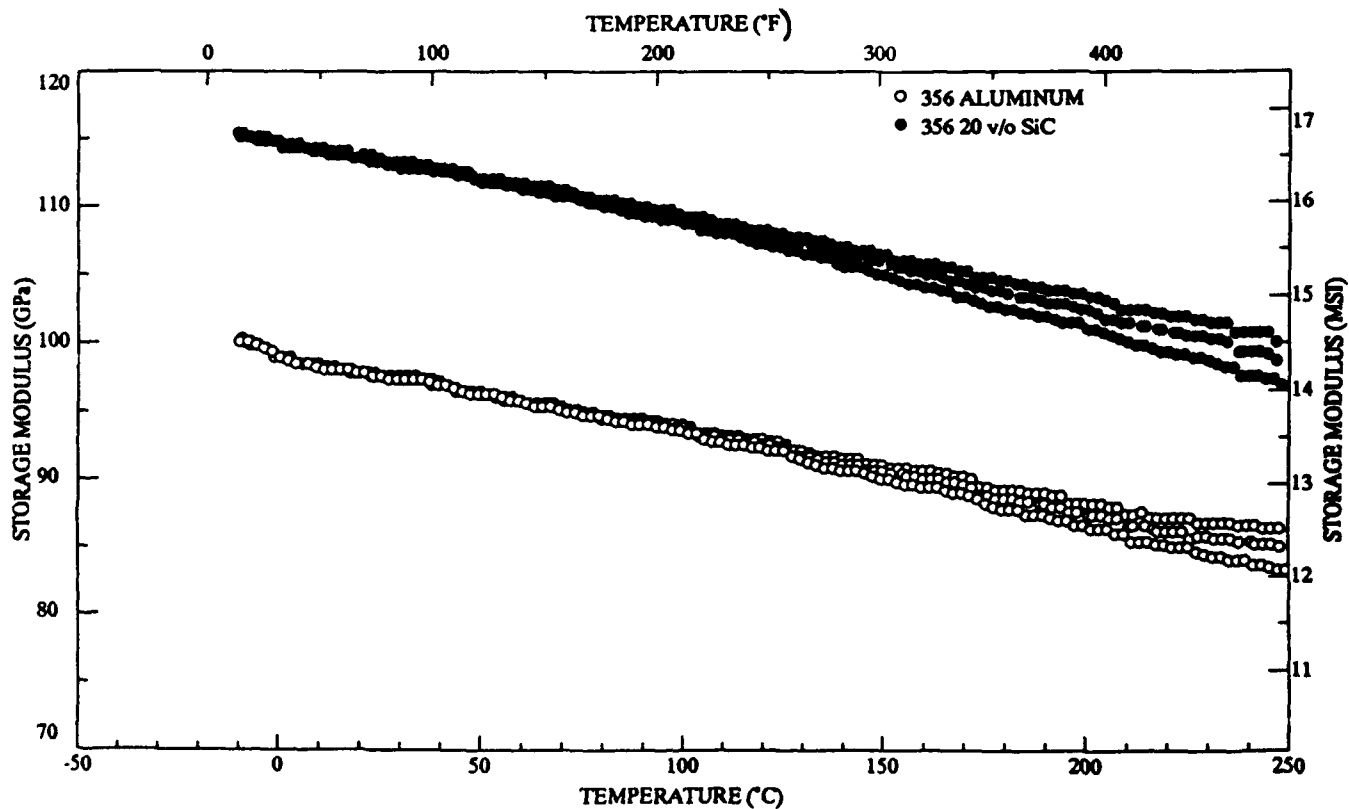


Fig. 9. The effect of frequency on the storage modulus of A356 aluminum matrix composites measured at 0.1, 1, and 10 Hz with the temperature increasing 1°C per minute.

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| 13. ABSTRACT (Maximum 200 words) Ceramic reinforced aluminum alloys exhibit a unique combination of properties not found in monolithic aluminum alloys. The addition of high modulus ceramic particles to conventional aluminum alloys results in increased strength, elastic modulus and wear resistance. Because of these desirable engineering properties the damping capacity and storage modulus was measured as a function of ceramic volume fraction, temperature and frequency. Two Al-Si-Mg matrix composites were studied which included the wrought alloy 6061-T6 with 0 to 0.2 volume fraction of Al ₂ O ₃ particles and the casting alloy A356-T6 with 0 to 0.2 volume fraction of SiC particles. They were manufactured by a process which is simpler and less costly than previously developed techniques for manufacturing metal matrix composites. The damping capacity and storage modulus were measured at 0.1, 1 and 10 Hz while the temperature was varied from -10 to 250°C. It was found that the cast matrix has a higher damping capacity than the wrought matrix above 100°C, possibly due to the presence of silicon in the matrix which lowers the grain boundary transition peak. The storage modulus and damping capacity increased with increasing reinforcement content. These results are consistent with other work done on ceramic reinforced aluminum alloys. | | | |
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